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Changing characteristics of land cover, landscape pattern and ecosystem services in the Bohai Rim region of China

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Since the Anthropocene, ecosystems have been continuously deteriorating due to global climate change and human intervention. Exploring the changing characteristics of land use/land cover (LULC), landscape pattern and ecosystem service (ES) and their drivers is crucial for regional ecosystem management and sustainable development. Taking the Bohai Rim region of China as an example, we used the land use transfer matrix, landscape pattern index and InVEST model to analyze the changing characteristics of LULC, landscape pattern and six key ESs [crop production (CP), water yield (WY), carbon storage (CS), soil conservation (SC), habitat quality (HQ), landscape aesthetics (LA)] during 2000−2020. Detailed analysis of the natural and anthropogenic factors affecting the landscape pattern and ES changes has been considered in this study. The results show that the areas of forest, water and impervious land increased, while those of cropland, shrubs, grassland and barren land decreased during 2000−2020. The landscape was fragmented, complex and decentralized during 2000−2015, while the three trends eased during 2015−2020. From 2000 to 2020, CP, WY, and SC capacity show an increasing trend, while CS, HQ, and LA capacity tend to a decline. Natural factors (e.g., precipitation, temperature, altitude) and human factors (e.g., technological progress, policy changes, and LULC forms) are the main factors affecting landscape pattern and ESs. The present study can provide theoretical basis for ecological restoration, ecological product value realization, and land planning in the typical developed urban area.

KEYWORDS

land use/land cover, landscape pattern, ecosystem service, Bohai Rim region, InVEST model

1 Introduction

Land is dynamic, its monitoring provides information about the human impacts on natural ecosystems environment, socio-economics and policies. Land use/Land cover (LULC) change is related to many ecological problems, such as soil erosion, land desertification and biodiversity loss (Zhang et al., 2020). It changes the supply of ecosystem products and services by affecting ecosystem structure and processes (e.g., vegetation cover, carbon sources and sinks), and has become the most important driving force affecting landscape pattern and ecosystem service (ES) (Assesment, 2005). Human estimated that LULC change has affected almost a third (32%) of the global land area in just 6 decades (1960–2019) and the area affected by global LULC change is nearly four times greater than previously thought (Winkler et al., 2021). A finite land area implies that fulfilling sustainable development goals requires increasing land-use efficiency of both storing carbon and producing food (Searchinger et al., 2018). Quantifying the dynamics of LULC change is critical in tackling global societal challenges such as food security, climate change, and biodiversity loss.

Landscape pattern refers to the structural composition and spatial configuration of landscape elements (forests, cropland, cities, etc.) (Wang et al., 2022), which is used to describe how landscape elements are spatially distributed and interconnected (Fu et al., 2022). Landscape pattern is influenced by human activities and climate change, its changes at the regional scale can directly affect energy flow and material circulation of ecosystem (Teutschbein et al., 2018), thus influencing the effects of ESs (Shao et al., 2023). The knowledge of the landscape pattern changes is the basis for comprehensively understanding regional ecological and environment changes, identifying ecological risks (Jiang et al., 2023), and rational planning LULC policies reasonably (van der Plas et al., 2019). Therefore, a comprehensive quantification of global landscape fragmentation is urgently required to guide landscape protection and restoration policies (Ma et al., 2023).

ESs refer to the benefits that humans obtain from ecosystems, typically divided into provisioning, supporting, regulating and cultural services (Assesment, 2005). ESs are considered as a bridge between natural ecosystems and human societies. The strategic planning for ESs could reduce tradeoffs between environmental quality and development (Bai et al., 2018). However, ESs have been continuously degraded since the Anthropocene as a result of global climate change and human intervention (Liu et al., 2024a). The Millennium Ecosystem Assessment (MA) report points out more than 60% of the world's ecosystems are currently or have already degraded (Assesment, 2005). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) found that 14 of 18 ecosystem components have declined since 1970 (Liu et al., 2022a). Therefore, it is necessary to accurately assess the spatiotemporal distribution of ESs and identify their potential drivers. This is the basis for avoiding the continuous degradation of ESs and the prerequisite for optimizing land use policies and delineating ecological red lines (Jiang et al., 2019; Ouyang et al., 2016).

The study of landscape heterogeneity is the focus of landscape pattern analysis and the landscape pattern indices are usually used to quantitatively evaluate regional landscape patterns, describe the spatial morphology, structure and heterogeneity of regional landscapes (Li et al., 2017). Currently, the research on landscape pattern has expanded to the fields of landscape ecological risk, ecological security pattern, ecological restoration, and has become the core of landscape ecology research. After the discussion of concepts, connotations and classification methods (Costanza et al., 1997; Fisher et al., 2009), the research on ESs has mainly focused on trade-offs and synergies, ecosystem service bundles (ESB). There are two main types of evaluation methods for ESs, namely, the value and the material quality methods. The material quantity method can objectively reflect the formation mechanism of ESs. The evaluation results are objective, stable, highly reliable, and do not change dramatically with the scarcity of ES. In particular, assessments using satellite remote sensing data have the advantages of finer spatial resolution, more comprehensive coverage and better temporal monitoring capabilities compared to traditional administrative unit-scale assessments. They avoid the locality and partiality that may exist in ground surveys and can more effectively identify the spatial distribution and changing patterns of ESs. The InVEST model can evaluate a wide range of ESs and can be combined with multi-source data, which has been widely used globally. However, existing studies on landscape patterns and ESs are mostly single-type studies, lacking systematic studies combining the two. At the same time, most studies are concentrated at a single city scale, with fewer studies at the city cluster scale, and they mostly concentrated in metropolitan areas such as the Yangtze River Delta and the Pearl River Delta, lacking studies on a broader scale of urban agglomerations. In addition, most studies focus on terrestrial ESs, with fewer studies on coastal and offshore ESs (Liu et al., 2020).

The Bohai Rim region is a key area in the Beijing-Tianjin-Hebei coordinated economic development strategy, and is rich in coastal ecological resources, with numerous types of estuarine deltas and coastal wetland reserves. However, it is also an ecologically fragile area. Since the area is a natural semi-enclosed bay surrounded by land on three sides, it has inherent characteristics such as insufficient hydrodynamics and weak water exchange capacity. In recent years, with the dual impact of global climate change and rapid urbanization, a series of ecological and environmental problems have emerged, including increased land pollution emissions, serious industrial and agricultural pollution (Zhao et al., 2021), fragmentation and isolation of coastal key belt landscapes, decreased ecological connectivity (Liu et al., 2020), and a significant reduction in natural wetland area (Wang et al., 2021). At present, it is urgent to conduct in-depth research on the landscape pattern and ESs in the Bohai Rim region.

In this study, we quantitatively assessed six landscape pattern indices and six ESs in the Bohai Rim region based on the analysis of LULC changes from 2000 to 2020 using Fragstats software, InVEST model, statistical data and landscape indicator assessment. Here, we focused to (1) clarify the changing characteristics of LULC, landscape patterns and ESs in the Bohai Rim region, (2) analyze the possible drivers affecting their spatial and temporal distributions, (3) propose detailed ecological management recommendations for different key zones in the Bohai Rim region.

2 Materials and methods

2.1 Study area

The Bohai Rim region is an important industrial and agricultural base in China, with rich agricultural, mineral, oil and gas and tourism resources. This region, centered on Beijing and Tianjin, is an important economic zone in eastern China with a concentrated population and increasingly concentrated industries. With a variety of ecosystems, including estuarine delta wetlands, cropland, breeding ponds, salt flats, forests, coastal mudflats and towns, the Bohai Rim region is an important part of the ecosystems in northern China and provides a wide range of ESs (Ning et al., 2011). With the rapid development of urbanization and industrialization in the Bohai Rim region, coastal development activities have become increasingly frequent, and LULC patterns have changed significantly. In addition, the Bohai Sea is surrounded by land on three sides, and there are problems such as innate hydrodynamic insufficiency and weak exchange capacity of water bodies. Global climate change and human activities have exposed the ecological environment in the Bohai Rim region to multiple risks such as coastal wetland shrinkage, nearshore soil salinization, biodiversity reduction, and water environment

deterioration. The Bohai Rim region studied in this article includes 15 coastal cities, including Tianjin, Hebei Province (Qinhuangdao, Tangshan, Cangzhou), Shandong Province (Yantai, Weihai, Dongying, Qingdao, Binzhou, Weifang), and Liaoning Province (Dalian, Yingkou, Panjin, Jinzhou, and Huludao) (Figure 1).

2.2 Data sources and processing

The main data of this study includes two categories: spatial data and statistical data. All spatial data were uniformly converted to the WGS_1984_UTM_50N coordinate system, and specific data information is shown in Table 1. Based on current situation of study area, we reclassified the snow land in the original LULC data into barren land and the wetland into water, which is divided into 7 types: cropland, forest, shrub, grassland, water, barren land, and impervious land. The MOD16A2GF product has a temporal resolution of 8 days, and the MOD13A3 product is monthly NDVI raster data. The two are batch projected by MRT (MODIS Reprojection Tools) software, and the Maximum Value Composites method was used to form the PET and NDVI datasets of each year. DEM data was filled in ArcGIS software. The final assessment results of each ES are at a resolution of 30 m.
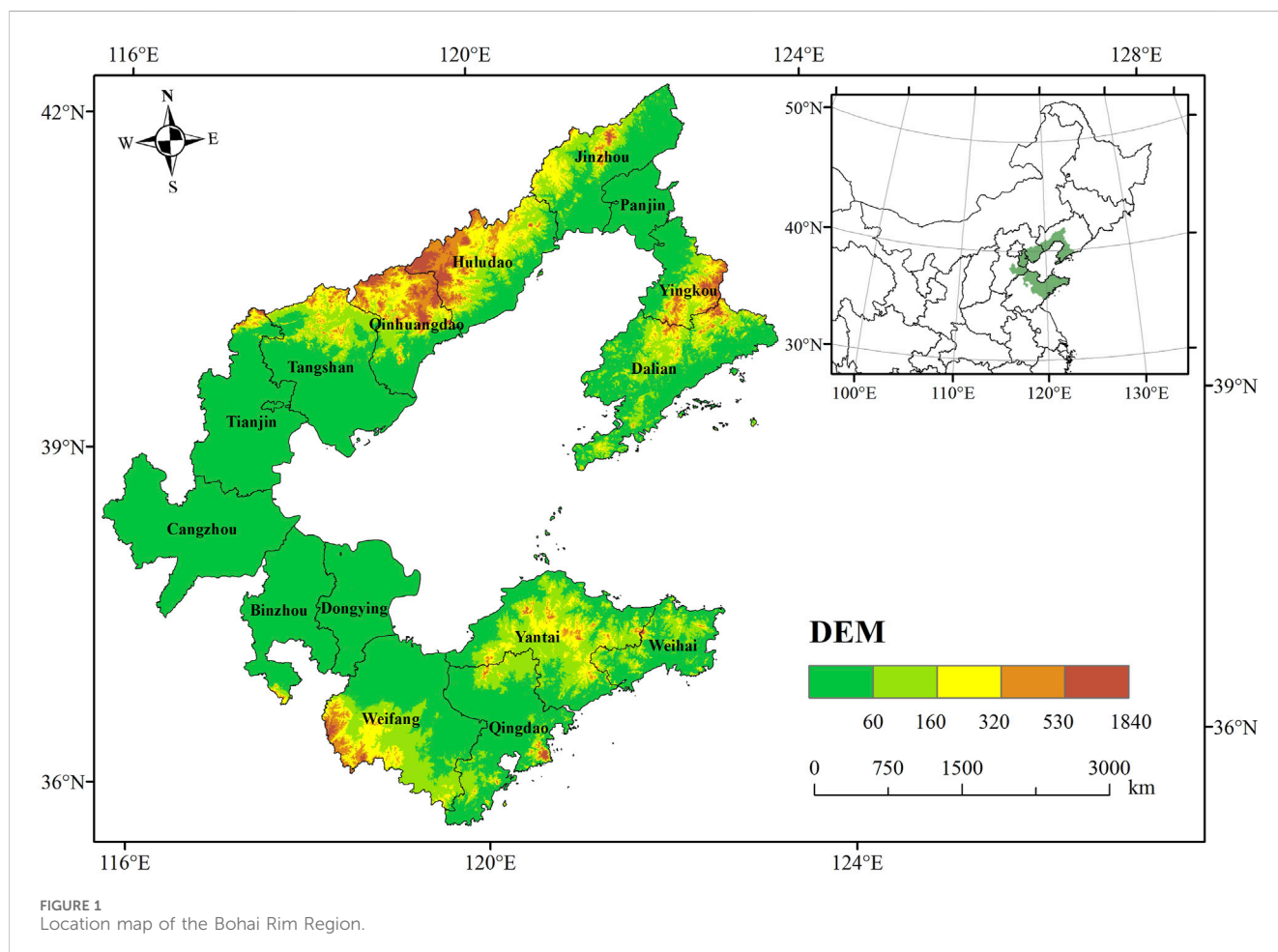

FIGURE 1
Location map of the Bohai Rim Region.

TABLE 1 Data sources and descriptions.

Data types	Application	Format	Data sources	Resolution
LULC	WY, CS, SC, HQ, LA	Raster	CLCD Land Use Dataset (https://zenodo.org/records/5816591#.ZAWM3BVBy5c)	30 m
Average annual rainfall	WY, SC	Raster	National Earth System Science Data Center (https://www.geodata.cn/)	1 km
Potential evapotranspiration	WY	Raster	MODIS Global Land Evapotranspiration Product MOD16A2GF (https://ladsweb.modaps.eosdis.nasa.gov/search/)	500 m
DEM	SC	Raster	Geospatial Data Cloud (https://www.gscloud.cn/)	30 m
Soil data	WY, SC	Raster	World Soil Database (HWSD) (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/)	1 km
NDVI	CP	Raster	MODIS Normalized Difference Vegetation Index MOD13A3 (https://ladsweb.modaps.eosdis.nasa.gov/search/)	1 km
Root restriction layer depth	WY	Raster	Data of "Bedrock Depth Map of China with a Spatial Resolution of 100 m" (https://doi.org/10.1038/s41597-019-0345-6)	1 km
Administrative boundaries	CP, WY, CS、SC, HQ, LA	Vector	Resources and Environmental Science and Data Center, Chinese Academy of Sciences (https://www.resdc.cn/)	——
Basin boundaries	WY, SC	Vector	HydroBASINS (http://hydrosheds.org/)	——
Road data	HQ	Vector	Peking University School of Urban and Environmental Sciences Geographic Data Platform (http://geodata.pku.edu.cn)	——
Crop production	CP	Statistical data	Statistical Yearbook	——

TABLE 2 Landscape pattern index and its ecological significance.

Indicator name	Indicator type	Meaning of indicators	Application scale
Patch density (PD)	Fragmentation	The number of patches per unit area is an important indicator for describing landscape fragmentation. The larger the PD, the greater the degree of fragmentation	Patch, Landscape
Edge Density (ED)	Complexity	It refers to the edge length between patches of heterogeneous landscape elements per unit area of the overall landscape, which can reflect the complexity of the landscape to a certain extent	Patch, Landscape
Landscape shape index (LSI)	Complexity	It is used to reflect the complexity of the landscape. The larger the LSI value, the greater the complexity of the landscape	Patch, Landscape
Aggregation index (AI)	Aggregation	It indicates the degree of patch agglomeration within a landscape area. The larger the AI value, the greater the degree of aggregation of different types of patches in the landscape	Patch, Landscape
Contagion (CONTAG)	Aggregation	It describes the aggregation degree or extension trend of different patch types in the landscape. The larger the CONTAG value, the greater the aggregation degree of different types of patches in the landscape	Landscape
Shannon Diversity Index (SHDI)	Fragmentation	It reflects the fragmentation of the landscape and is particularly sensitive to the uneven distribution of patch types in the landscape. The higher the degree of fragmentation, the greater the information content of its uncertainty, and the higher the calculated SHDI	Landscape

2.3 Research methods

2.3.1 LULC change analysis

The method of LULC transfer matrix is used to study LULC change, and the application of its results can clearly represent the specific structural characteristics of LULC and the changes of functional types of LULC. The expression is shown in Equation 1:

$$S_{ij} = \begin{bmatrix} S_{ij} & \cdots & S_{in} \\ \vdots & \ddots & \vdots \\ S_{nj} & \cdots & S_{nn} \end{bmatrix}, \quad (i, j = 1, 2 \ldots, n) \quad (1)$$

In the formula, S represents the area (km^2), S_{ij} represents the area transfer matrix, n represents the LULC type, i and j

represent different LULC types during the study period. If i = j represents the area of LULC type that has not changed (Lai et al., 2016).

2.3.2 Landscape pattern index selection

This study selected patch density (PD), edge density (ED), landscape shape index (LSI), aggregation index (AI), contagion (CONTAG), and Shannon's diversity index (SHDI) from two aspects: patch metrics and landscape metrics. They were used to reflect landscape fragmentation, complexity, and aggregation. Detailed information of each index is shown in Table 2. All landscape pattern indices were calculated in Fragstats 4.2 software.

TABLE 3 Overview of ecosystem services assessed in this study.

Level 1 classification	Level 2 classification	Abbreviation	Assessment methods
Provisioning services	Crop production	CP	Statistical Methods
	Water yield	WY	InVEST
Regulating services	Carbon storage	CS	InVEST
	Soil conservation	SC	InVEST
Supporting services	Habitat quality	HQ	InVEST
Cultural services	Landscape aesthetics	LA	Landscape indicator assessment

2.3.3 Ecosystem services assessment

Based on the ES classification system proposed by The Millennium Ecosystem Assessment (MA), and according to the actual situation and research foundation of the Bohai Rim region, six important ESs were selected: crop production (CP), water yield (WY), carbon storage (CS), soil conservation (SC), habitat quality (HQ), and landscape aesthetics (LA) (Table 3).

CP and WY are Provisioning services. In the past 20 years, cropland in the Bohai Rim region has been continuously decreasing, the coastal land has been salinized, and extreme droughts and floods disasters have occurred frequently, which has a great impact on CP. Therefore, evaluating CP and WY is of great significance to ensuring the wellbeing of the people's lives. The coastal wetlands in the Bohai Rim region have been seriously degraded, resulting in a decrease in CS capacity and weakened flood control capacity. Deforestation and inappropriate construction activities have increased the risk of soil erosion and caused the loss of fertile topsoil. Therefore, CS and SC were selected as the research objects of regulating services. The coastal zone around the Bohai Rim region has been seriously eroded and faces multiple ecological risks such as eutrophication and biodiversity degradation. Therefore, HQ was selected as the research object of supporting services. The Bohai Rim region has a wide variety of landforms, covering mountains, plains, estuaries, coasts, islands, wetlands, etc., which is a microcosm of China's landform diversity. Therefore, LA were selected to represent the cultural services of the region.

2.3.3.1 CP

The CP data obtained from the statistical yearbooks of provinces and cities in the Bohai Rim region includes grains, beans, and potatoes, all of which are produced on cropland. Previous studies have shown that there is a significant linear relationship between CP and NDVI, therefore CP is allocated to cropland grids according to the NDVI value (Equation 2).

$$G_i = G_{sum} \times \frac{NDVI_i}{NDVI_{sum}} \qquad (2)$$

In the formula: G_i is the crop production in the i-grid (kg); G_{sum} is the total crop production in the study area (kg); $NDVI_i$ is the normalized vegetation index of the i-grid; $NDVI_{sum}$ is the sum of NDVI values for cropland in the study area.

2.3.3.2 WY

WY affects human production and life in various ways. This study uses the Annual Water Yield module in the InVEST model to estimate WY services, the specific model parameters are presented in the Supplementary Table S1. This module is based on the principle of water balance and uses the difference between regional rainfall and evapotranspiration to determine WY (Equation 3) (Hu et al., 2019).

$$Y(x) = P(x) - AET(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \times P(x) \qquad (3)$$

In the formula: $Y(x)$ is the annual water yield of regional unit x (mm), $P(x)$ and $AET(x)$ are the annual rainfall and actual evapotranspiration of grid x (mm), respectively.

2.3.3.3 CS

The widely distributed wetland ecosystems in the Bohai Rim region are particularly important carbon sinks that can store a large amount of organic carbon. The Carbon Storage module of the InVEST has been widely used to evaluate CS. It divides the CS of each LULC type into four basic carbon pools: aboveground biomass carbon (C_{above}), belowground biomass carbon (C_{below}), soil organic carbon (C_{soil}), dead organic matter carbon (C_{dead}) (Zhu et al., 2020), The calculation formula is as follows (Equations 4, 5):

$$C_i = C_{i-above} + C_{i-below} + C_{i-soil} + C_{i-dead} \qquad (4)$$

$$C_{tot} = \sum_{i=1}^{n} C_i \times S_i \qquad (5)$$

In the formula: i represents a certain LULC type; $C_{i-above}$ is the aboveground biomass carbon density (t/km²) of LULC type i; $C_{i-below}$ is the underground biomass carbon density (t/km²) of LULC type i; C_{i-soil} is the soil carbon density (t/km²) of LULC type i; C_{i-dead} is the dead organic carbon density (t/km²) of LULC type i; C_{tot} is the total carbon storage(t) of the ecosystem, S_i is the area (km²) of LULC type i, n is the number of LULC types, which is 7 in this study. Carbon density data was obtained by consulting relevant literature (Li et al., 2020; Xia et al., 2023a; Zhu et al., 2022) (Supplementary Table S2).

2.3.3.4 SC

The InVEST model Sediment Delivery Ratio module (SDR) was used to simulate and evaluate SC. This module is a spatial display model for raster calculation. Based on the modified general soil loss equation, it uses LULC data, DEM data, soil property data,

TABLE 4 Area of LULC types in the Bohai Rim Area (km²).

LULC types	2000	2005	2010	2015	2020
Cropland	102,143.46	100,083.76	97,087.70	94,048.48	92,258.73
Forest	16,965.44	16,742.20	17,205.35	17,842.78	17,731.20
Shrub	1.14	0.59	0.64	1.96	1.18
Grassland	3,993.77	3,657.58	3,426.04	3,043.73	2684.97
Water	5,238.98	5,990.00	6,005.28	5,959.92	6,150.36
Barren	2,227.22	2,059.85	1,796.64	1,396.36	320.19
Impervious	21,400.04	23,436.06	26,448.39	29,676.83	32,823.41
Total	151,970.05	151,970.05	151,970.05	151,970.05	151,970.05

precipitation data, vegetation cover factors, soil and water conservation measures factors to calculate the annual soil erosion and sediment transport rate of the grid, and then simulates the raster soil erosion and sediment transport process (Liu et al., 2023), The calculation formula is as follows (Equations 6–8):

$$S_x = RKLS_x\text{-}USLE_x \qquad (6)$$

$$RKLS_x = R_x \times K_x \times L_n \times S_x \qquad (7)$$

$$USLE_x = R_x \times K_x \times L_n \times S_x \times C_x \times P_x \qquad (8)$$

In the formula: S_x is the SC capacity(t); $RKLS_x$ is the potential soil erosion capacity(t); $USLE_x$ is the actual soil erosion capacity(t); R_x is the precipitation erosion rate; L_n is the slope length gradient factor; S_x is the slope gradient factor; K_x is the soil erodibility factor. Among them, R_x factor is calculated based on the R value calculation model established by Zhang Wenbo (Zhang and Fu, 2003) and the annual average precipitation. K_x factor is calculated using the soil erodibility K value calculation model established by Wischmeier (Wischmeier et al., 1971) combined with soil data. C_x、 P_x values are determined with reference to the InVEST Chinese manual and relevant literature (Liu et al., 2024b) (Supplementary Table S3).

2.3.3.5 HQ

The maintenance of biodiversity is closely related to HQ. Use the Habitat Quality module of the InVEST to evaluate the HQ index, with a range of values from 0 to 1. The larger the value, the higher the HQ. The formula is as follows (Equation 9):

$$Q_{xj} = H_j \left(1 \text{-} \frac{D_{xj}^z}{D_{xj}^z + k^z} \right) \qquad (9)$$

In the formula, Q_{xj} is the habitat quality of grid x in LULC type j; H_j is the habitat suitability of LULC type j; D_{xj} is the habitat stress level of grid x in LULC type j, k is a semi saturation constant; z is a normalized constant. This study determined the parameters based on relevant literature (Deng et al., 2018) (Supplementary Tables S4, S5).

2.3.3.6 LA

LA refers to the benefits and comfort that individuals gain from interacting with visually pleasing natural landscapes, and is an intangible cultural service (Langemeyer et al., 2018). The evaluation of LA is often based on two criteria: naturalness and

landscape diversity. Naturalness refers to the degree of human interference, while landscape diversity reflects the diversity of landscape structure (Frank et al., 2013). Naturalness is quantified using the chlorophyll index from 1 (natural) to 7 (artificial) (Xia et al., 2023b). Landscape diversity was quantified using the Shannon's diversity index (SHDI) in Fragstats 4.2 software. The final LA index was obtained by adding the normalized values of naturalness and landscape diversity (Equation 10).

$$LA_i = (NT_i + LD_i)/2 \qquad (10)$$

In the formula: LA_i is the landscape aesthetics value of the i grid; NT_i is the normalized naturalness value of the i grid; LD_i is the normalized SHDI value of the i grid. All three indicators are standardized to 1–100.

3 Results

3.1 LULC distribution characteristics

The LULC types in the Bohai Rim region are mainly cropland land, impervious land and forest, among which cropland accounts for the largest proportion, exceeding 60% at all stages of the study period. Impervious land and forest account for more than 14% and 11%. Shrubs account for the smallest proportion, with an average area of only 1.1 km² over 20 years (Table 4).

From the perspective of the spatial distribution (Figure 2), cropland is widely distributed, covering most of the Bohai Rim region; forest is mainly distributed in the north and northwest, shrubs and grasslands are mainly distributed in the northwest of the study area and the northern area of Shandong Peninsula; water is mainly distributed on the edge of the Bohai Bay; barren land is mainly distributed in the edge of Laizhou Bay and Bohai Bay, as well as the Yellow River Delta; impervious land are mainly distributed in the marginal areas of the coast and the city centers.

From the perspective of the temporal distribution, the proportions of forest, water and impervious land have expanded from 11.16%, 3.45%, 14.08% in 2000 to 11.67%, 4.05%, 21.60% in 2020; while the area proportions of cropland, grassland and barren land decreased from 67.21%, 2.63%, 1.47%–60.71%, 1.77% and 0.21%. From 2000 to 2020,
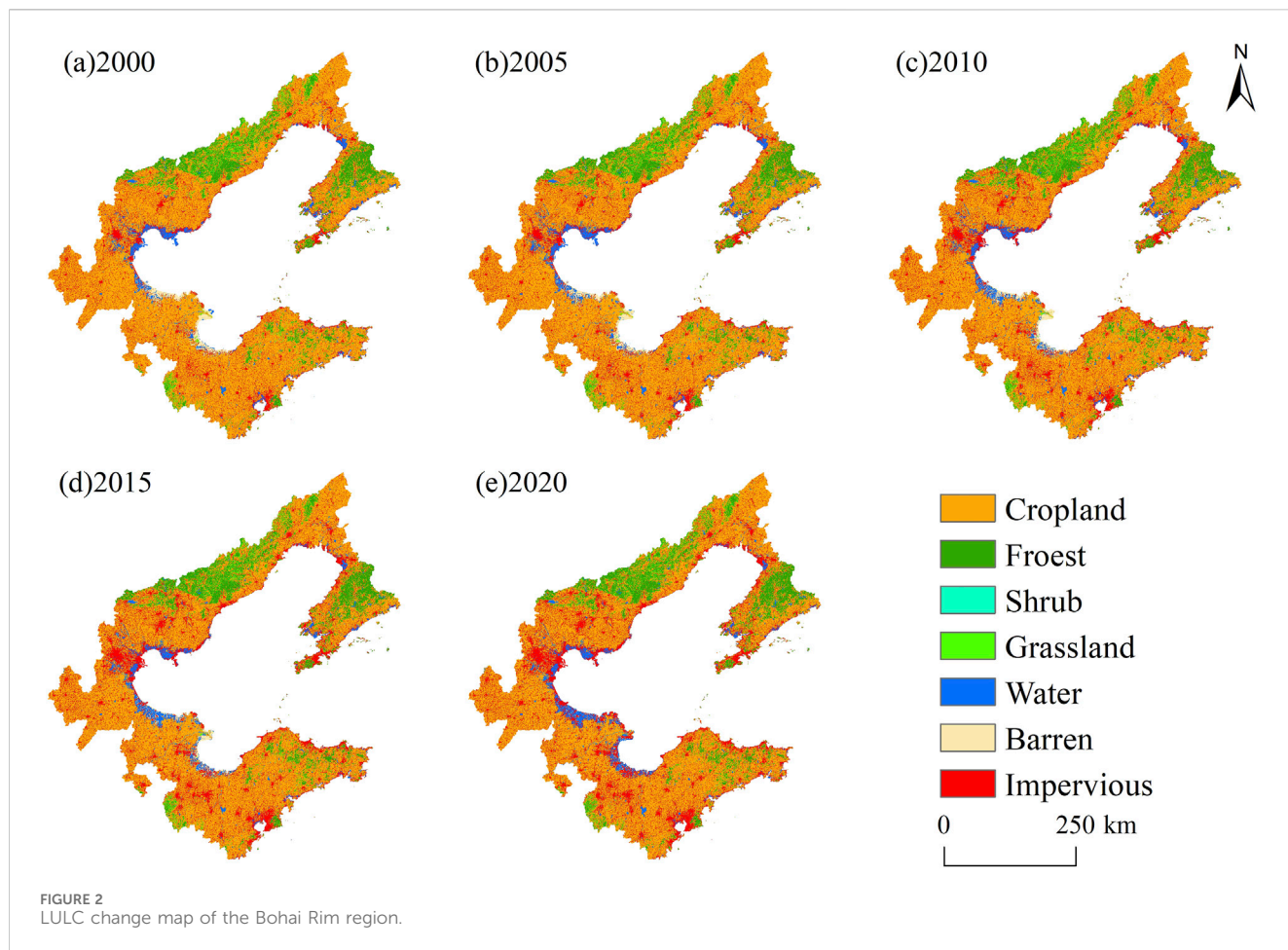
FIGURE 2
LULC change map of the Bohai Rim region.

**TABLE 5 LULC change transfer matrix during 2000-2020 (km²).**

2000/2020	Cropland	Forest	Shrub	Grassland	Water	Barren	Impervious	Initial area
Cropland	89,301.68	1,490.55	0.00	541.89	1,360.23	24.21	9,424.89	102,143.46
Forest	1,322.72	15,409.10	0.69	79.13	1.92	0.14	151.74	16,965.44
Shrub	0.02	0.23	0.20	0.68	0.00	0.00	0.00	1.14
Grassland	882.84	826.52	0.28	2,060.70	36.42	18.89	168.11	3,993.77
Water	509.56	4.30	0.00	0.62	3,126.99	28.52	1,568.98	5,238.98
Barren	113.10	0.01	0.00	1.70	1,002.22	239.17	871.02	2,227.22
Impervious	128.80	0.50	0.00	0.25	622.57	9.26	20,638.67	21,400.04
Final area	92,258.73	17,731.20	1.18	2,684.97	6,150.36	320.19	32,823.41	151,970.05

the area of forest and shrub showed a trend of first decreasing and then expanding. This study further calculated the LULC transfer matrix (Table 5) and drew the LULC transfer Sankey diagram (Figure 3). During the study period, 12,841.78 km² of cropland was transferred out and 2,957.05 km² was transferred in, mainly transforming into impervious land, forest and water; 761.37 km² of impervious land was transferred out and 12,184.74 km² was transferred in, mainly from cropland and water. 1,556.34 km² of forest was transferred out and 2,322.11 km² was transferred in, mainly from cropland and water; 2,111.99 km² of water was

transferred out and 3,023.37 km² were transferred in, mainly from cropland and barren land. Overall, the LULC types in the Bohai Rim region changed drastically, mainly among cropland, impervious land, forest, and water.

3.2 Landscape pattern index characteristics

At the landscape metrics (Figure 4), PD and SHDI both increased from 2000 to 2015 and decreased from 2015 to 2020,
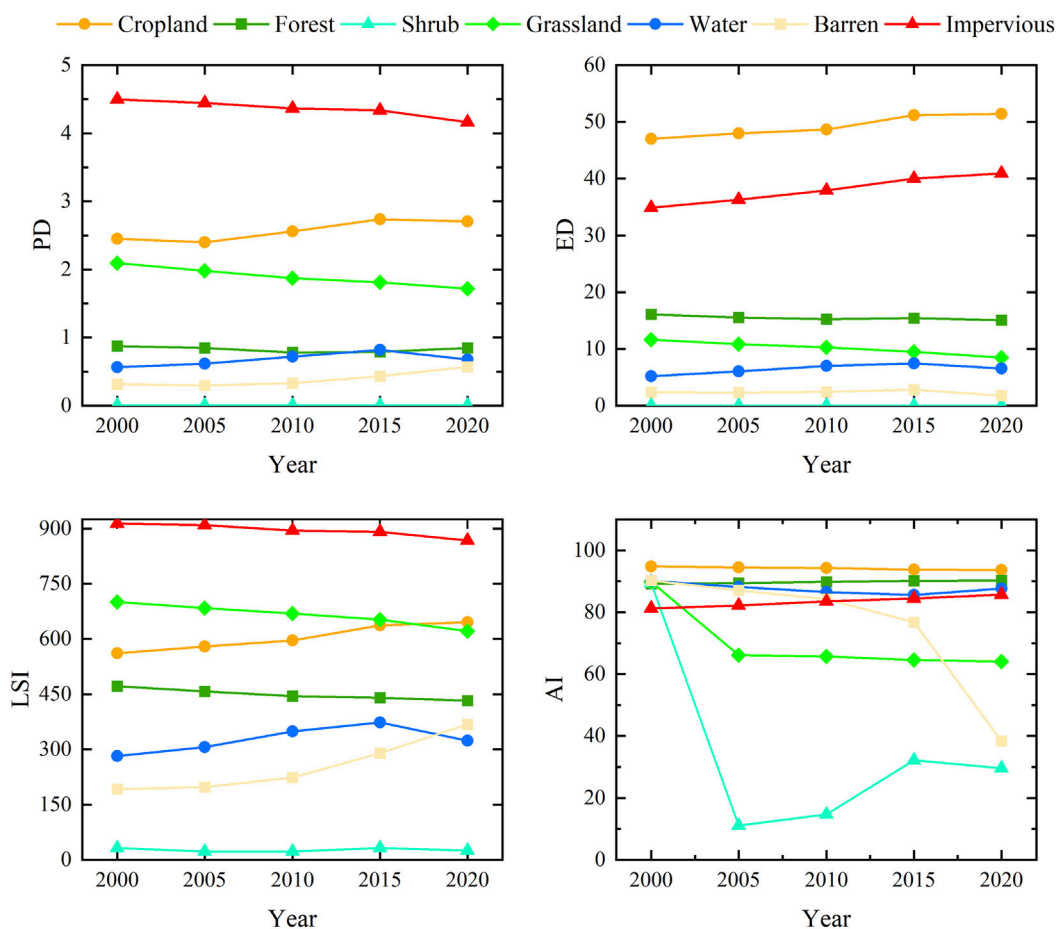
FIGURE 3
Sankey diagram of LULC changes in the Bohai Rim region.

FIGURE 4
Landscape pattern index changes at the landscape level in the Bohai Rim region.
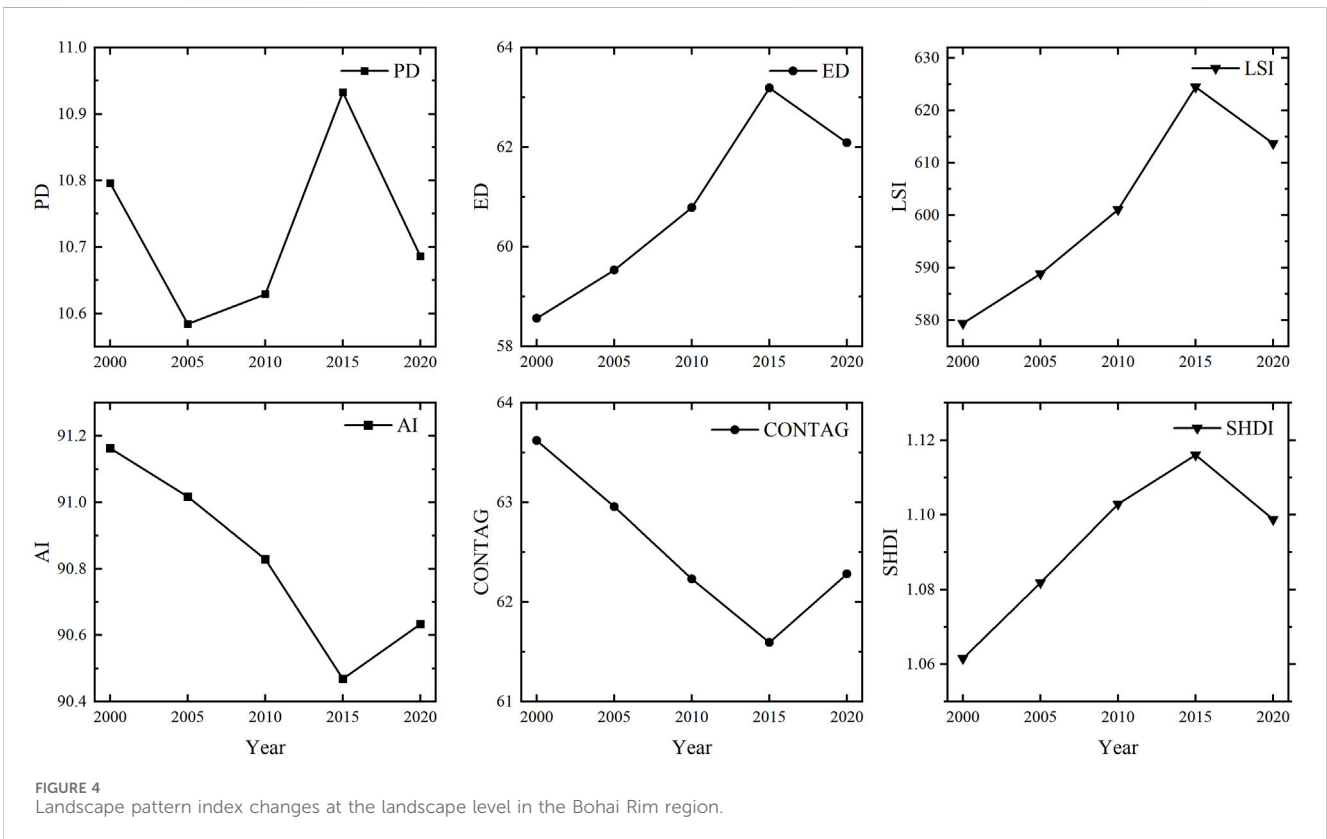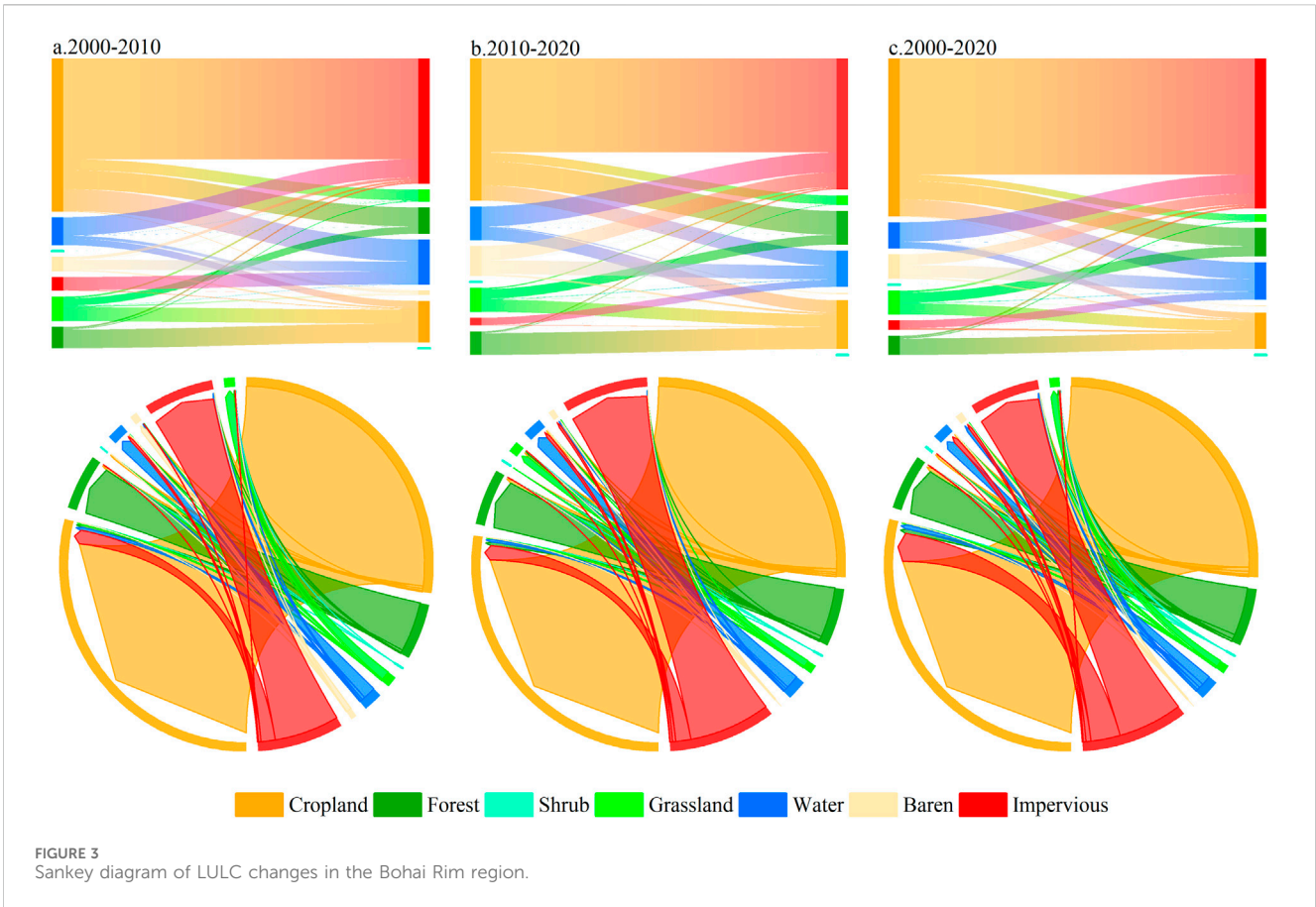
FIGURE 5
Landscape pattern index changes at the patch level in the Bohai Rim region.

indicating that the degree of regional landscape fragmentation first increased and then decreased. ED and LSI increased rapidly from 2000 to 2015 and decreased from 2015 to 2020, indicating that the landscape shape first became complex and then tended to be simplified. AI and CONTAG both decreased significantly from 2000 to 2015 and increased from 2015 to 2020, indicating that the connectivity between landscape patches weakened and the separation increased in the early stage, which was alleviated in the later stage.

At the patch metrics (Figure 5), PD, ED and LSI of cropland increased, while AI decreased, indicating that cropland landscape has an obvious trend of fragmentation, complexity and dispersion. PD of forest decreased from 2000 to 2010 and increased from 2010 to 2020, its ED and LSI continued to decrease, and AI continued to increase, indicating that the degree of fragmentation in forest first decreased and then increased, with a process of simplified shape and aggregation of patches. Shrubs have fewer patches, are easily affected by external conditions, and change erratically. PD, ED, LSI and AI of grassland continued to decrease. PD, ED and LSI of water increased from 2000 to 2015, then decreased slightly from 2015 to 2020, but were still higher than the level of 2000; its AI decreased during 2000–2015 and increased significantly from

2015 to 2020. PD and LSI of barren land increased, AI decreased, ED increased during 2000–2015 and decreased to a level lower than that in 2000 during 2015–2020. PD and LSI of the impervious land continued to decrease, while ED and AI continued to increase.
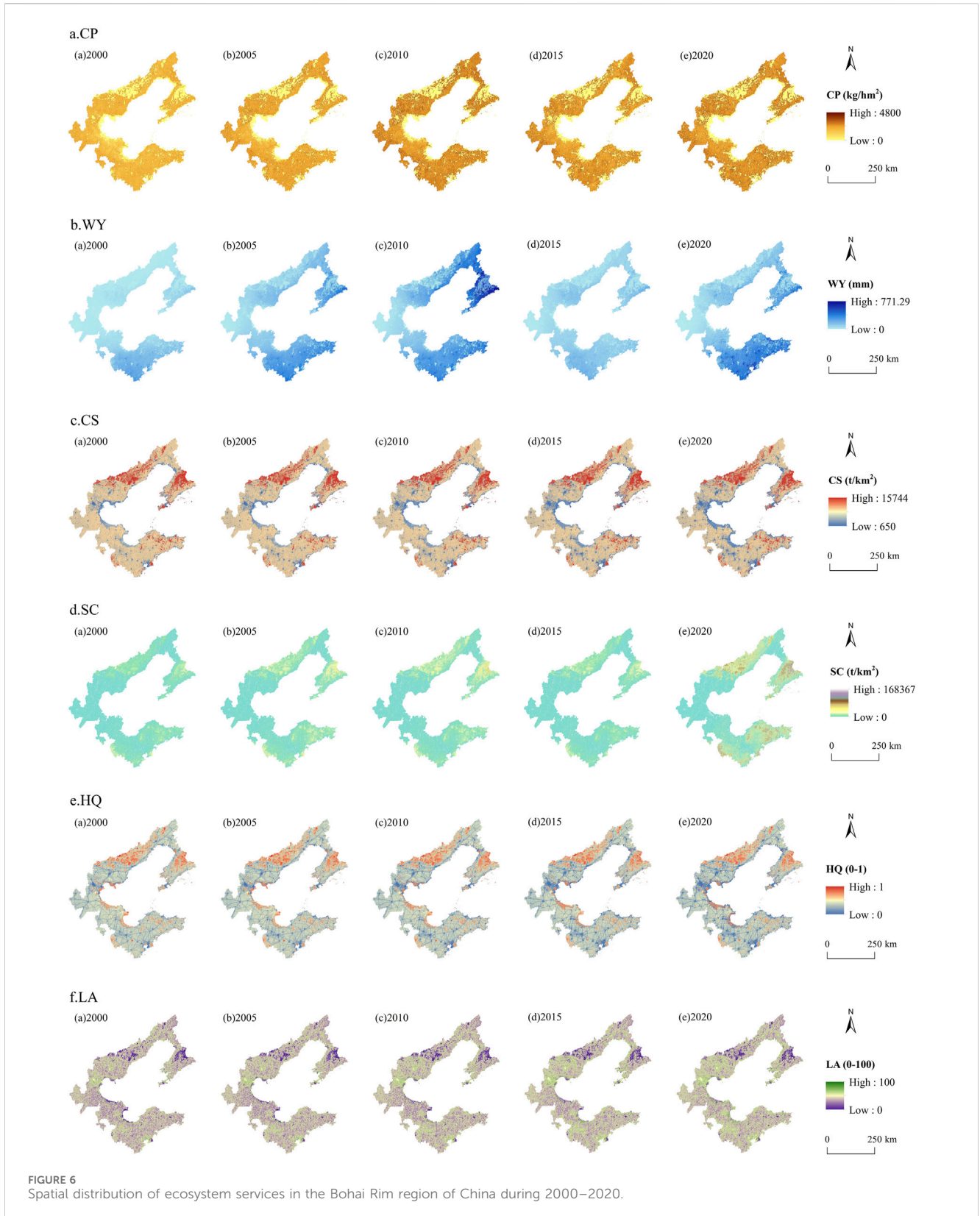
3.3 Distribution characteristics of ESs

3.3.1 Provisioning services
3.3.1.1 CP

In general, CP shows an increasing trend from 2000 to 2020 (Figure 6A). The total crop production in 2000, 2005, 2010, 2015 and 2020 was 2365.12wt, 2802.27wt, 3,265.03wt, 3,049.83wt, 3,139.67wt, and the yield per unit area was 1,526.20 kg/hm², 1808.29 kg/hm², 2106.91 kg/hm², 1968.04 kg/hm², 2026.01 kg/hm² respectively. CP continued to increase from 2000 to 2010, increasing by 38% in 2010 compared with 2000, and decreased slightly from 2010 to 2020.

3.3.1.2 WY

WY has generally shown an increasing trend (Figure 6B). The total water yield in 2000, 2005, 2010, 2015 and 2020 was 10.07 billion m³, 23.56 billion m³, 25.73 billion m³, 12.86 billion m³

FIGURE 6
Spatial distribution of ecosystem services in the Bohai Rim region of China during 2000−2020.

and 26.35 billion m³. In 2015, WY decreased by 12.863 billion m³ compared with 2010. The spatial distribution of WY in the Bohai Rim region is high in the north and south and low in the center. The high-value areas are mainly distributed in the Shandong Peninsula,

the coast of Liaodong Bay and the Liaodong Peninsula, while the low-value areas are mainly distributed in Tianjin, Cangzhou, the northern part of Qinhuangdao and Huludao, and the central and northern part of Dalian.

3.3.2 Regulating services
3.3.2.1 CS

From a temporal perspective, carbon storage shows a decreasing trend (Figure 6C). The total carbon storage in 2000, 2005, 2010, 2015 and 2020 was 134.87×10^7t, 132.50×10^7t, 130.20×10^7t, 127.96×10^7t, 125.51×10^7t. In the past 20 years, 9.37×10^7t carbon has been lost, with soil carbon storage losing the most, at 9.10×10^7t. Aboveground biomass carbon storage has increased by 0.03×10^7t over the past 20 years, which is due to the fact that the aboveground biomass carbon density of forest is large, and the forest area increased between 2000 and 2020. From a spatial perspective, CS distribution pattern in the Bohai Rim region was relatively consistent from 2000 to 2020, with no obvious spatial changes. Areas with higher CS are mainly distributed in the northern mountainous areas of Qinhuangdao and Huludao, as well as the central and northern areas of Dalian, with the highest value of 15,744 t/km². The LULC types in these areas are mainly forest, shrubs and grassland. The areas with lower CS are mainly distributed in the Bohai Bay, Laizhou Bay, Liaodong Bay coast and the central areas of various provinces and cities. The LULC types in these areas are mainly water and impervious land, with the lowest value of 650 t/km².

3.3.2.2 SC

(2) SC: From a temporal perspective, soil conservation generally showed an increasing trend (Figure 6D). The SC level in 2000, 2005, 2010, 2015 and 2020 were 3,579.86 t/km², 5,853.93 t/km², 6,463.65 t/km², 4,236.31 t/km² and 7,071.22 t/km². In 2015, SC significantly decreased, with a decrease of 33,848.90wt compared to 2010. From a spatial perspective, SC was generally low but locally high. Liaoning Province has the strongest SC capacity at 8,302.31 t/km², which is 1.53 times the average value of the Bohai Rim region. Yingkou has the highest average SC capacity at 13,866.25 t/km². Tianjin has the lowest SC capacity, which is 1,363.94 t/km², only 25% of the average value.

3.3.3 Supporting services
3.3.3.1 HQ

From a temporal perspective, HQ index has been declining (Figure 6E). The average HQ index in the study area in 2000, 2005, 2010, 2015 and 2020 was 0.39, 0.38, 0.37, 0.36 and 0.35. In the past 20 years, the HQ index has decreased by 10.26%, indicating that the overall HQ of the ecosystem in the Bohai Rim region has been deteriorating. From a spatial perspective, the HQ in the Bohai Rim region has significant spatial heterogeneity, with high values mainly distributed in Qinhuangdao, Dalian, Yingkou, Huludao, Bohai Bay and the coast of Laizhou Bay. Low values are mainly distributed in Qingdao, Tianjin, Cangzhou and Weifang. These areas have large populations, high human activity intensity, large demand for infrastructure construction, and rapid economic development, which drives the gradual expansion of non-habitat areas.

3.3.4 Cultural services
3.3.4.1 LA

From a temporal perspective, LA index in the Bohai Rim region has been continuously increasing (Figure 6F). The average LA index of the study area in 2000, 2005, 2010, 2015, and 2020 were 40.07, 40.81, 41.70, 42.70, and 43.56. From 2000 to 2020, the LA index increased by 8.71%, indicating that the quality of LA has continued to deteriorate. From a spatial perspective, Yingkou, Qinhuangdao, and Huludao have the lowest LA values, indicating that residents can gain more benefits and comfort from the interaction with the natural landscape in these areas. The higher cultural services in these areas can help realize the value of cultural ecological products, such as developing ecotourism, promoting cultural tourism consumption and creating characteristic tourism brands. Tianjin, Tangshan and Qingdao have the highest LA values. This means that the natural landscapes in these areas provide residents with lower spiritual comfort, which is not conducive to the realization of ecological product value and regional sustainable development.

4 Discussion

4.1 InVEST model results accuracy verification

The verification of the WY is based on the data from the Water Resources Bulletin. The actual water resources in the study area in 2000, 2005, 2010, 2015, and 2020 were 10.423 billion m³, 23.135 billion m³, 23.267 billion m³, 14.07 billion m³ and 23.54 billion m³ respectively. The error between the model simulation results and the actual water resources is controlled at around 10%, so the results are reliable.

The carbon density data of CS were considered in accordance with the following principles: the four basic carbon pool data were considered from published data obtained from field investigations. The missing data were used from neighboring regions. This approach and criteria ensured the credibility of the results to the greatest extent.

The assessment results obtained from the SC module were verified with reference to relevant research (Feng et al., 2022; Wang et al., 2022). Since the Bohai Rim region spans multiple watershed divisions, the results are also within the overall range. Therefore, it has a reasonable value.

The evaluation results of the HQ by province are basically consistent with the findings of Tianjin (Li et al., 2022b) and Dongying (Ding et al., 2021), with a difference of about 10%. In addition, the HQ change rate of Dongying from 2000 to 2020 is found to be consistent with the trends in the Yellow River Delta (Liu et al., 2022b), with a change rate of about 15.8%, this provides a good confidence.

4.2 Analysis of factors influencing landscape pattern and ESs

4.2.1 Analysis of factors influencing landscape patterns

In general, before 2015, landscape fragmentation increased, and the patch shapes tended to be complex and dispersed. This situation improved after 2015. The reasons for the landscape fragmentation, complexity, and dispersion from 2000 to 2015 include two aspects. First, intense human activities such

FIGURE 7
Schematic diagram of natural environment in the Bohai Rim region of China.
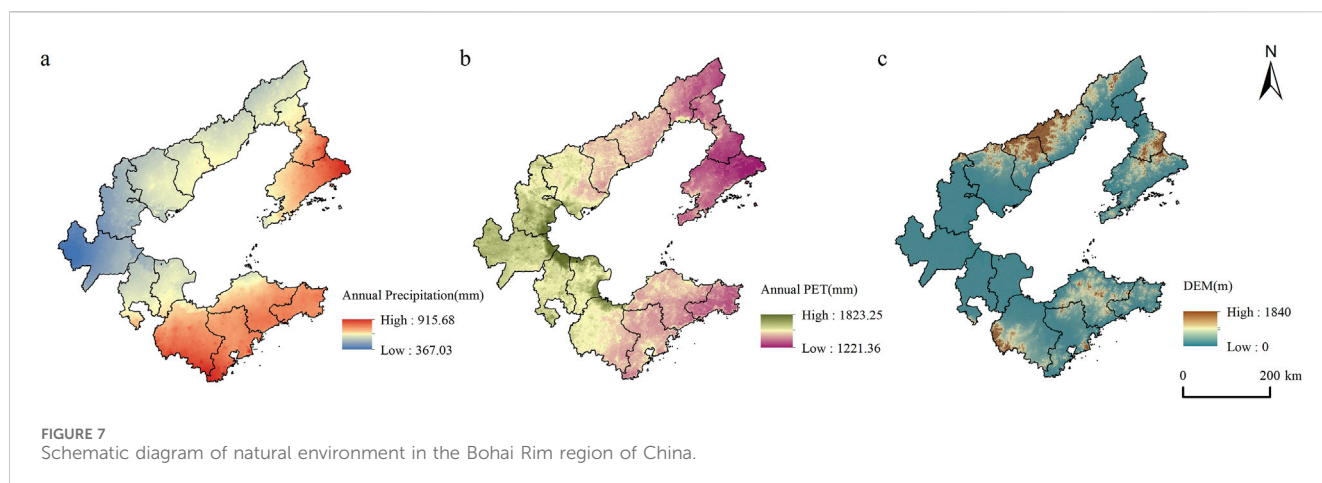
as cropland occupation, urban construction, and rail transit construction divided the originally coherent natural patches into discrete small patches. Second, returning cropland to forests and lakes, various reclamation activities have led to a significant transformation in LULC patterns, exacerbating the degree of regional landscape fragmentation, complexity and decentralization. In 2015, China issued the "Opinions on Accelerating the Construction of Ecological Civilization", to increase the forest, grassland and wetland coverage rate by 2020. The "National Land Planning Outline (2016–2030)" and the "National Agricultural Sustainable Development Plan (2015–2030)" followed strategies at the same time, both requiring strict ecological protection system. The fragmented patches cropland areas have been integrated; the main landscape types are considered as a large area. Highly urbanized areas continued to expand, and small built-up areas are integrated with large landscapes, making the landscape homogenized. The degree of patch aggregation was high, and the fragmentation and complexity of the landscape were alleviated.

The continuous policy of returning cropland to forest and the occupation of cropland have increased the fragmentation and complexity of the cropland landscape and reduced its aggregation. The policy of returning cropland to forest requires converting eligible sloping cropland with a degree of 25 or above into forests and grasslands, which has formed a larger area of fragmented forest in the later period (Hao et al., 2017), making the degree of forest fragmentation increased during 2010–2020. It can be seen from the LULC transfer matrix that the area of grassland transferred out is larger than the area transferred in, and the fragmented patches are converted into cropland and forest, which are integrated with the larger landscape. Therefore, the degree of landscape fragmentation of grassland continues to decrease, and patches become more simplified and dispersed. From 2000 to 2015, various human activities such as land reclamation, aquaculture, and reservoir construction, as well as the policy of returning cropland to lakes, have made the regional water landscape fragmented, complex, and decentralized. In 2015, China further increased its support for wetland protection, and the central government allocated $223.2 million in wetland subsidies, covering wetland protection

and restoration, returning cropland to wetlands, and ecological compensation. With the new relevant policies, the area and quantity of wetlands increased significantly from 2015 to 2020, expanding the connectivity between wetlands and making their shapes simpler. As a result, the fragmentation, complexity, and dispersion of water landscape patches were reduced. The area of barren land decreased while the impervious land expands year by year. Therefore, the landscape pattern of the two is opposite. In the process of barren land converting into impervious land, although the landscape pattern is fragmented, complex, and dispersed. The expansion of the impervious land increases the uniformity of its patches, reducing the degree of fragmentation and the complexity of the landscape, increasing the aggregation of patches.

4.2.2 Analysis of factors influencing ESs

The natural factors, precipitation, temperature and altitude are the main factors affecting ESs (Figure 7). In 2015, the average precipitation in the study area was only 562 mm, about 83% of that in 2010 (Figure 8), resulting in a decrease of 215.2wt in CP in 2015 compared with 2010, a decline of about 6.6%; WY decreased by 12.862 billion m^3 compared with 2010, a decline of about 50%; the decline in precipitation directly changed the precipitation runoff erosion rate (Zhang et al., 2022), that contributed decline of 2,227.34 t/km^2 in SC intensity in the Bohai Rim region, which is consistent with the Luan River Basin (Liu et al., 2023). The temperature mainly affects ESs through its influence on regional evapotranspiration. In 2015, the average temperature in the study area was 12.51°C, which was 0.81°C higher than in 2010 (Figure 8). This increased the potential evaporation of vegetation and significantly reduced the WY. The northern parts of Dalian and Huludao, the southern part of Yingkou in Liaoning Province are located at higher altitudes, with less urbanization and human activities. Vegetation coverage, soil thickness and biodiversity all increase with altitude, and the SC capacity is the strongest. Similarly, Yantai and the southwestern part of Weifang in Shandong Province are at higher altitudes, coupled with higher annual precipitation throughout the province, so the SC capacity is relatively strong. However, most areas of Hebei province and Tianjin are at a low altitude, with low vegetation coverage, few artificial protection
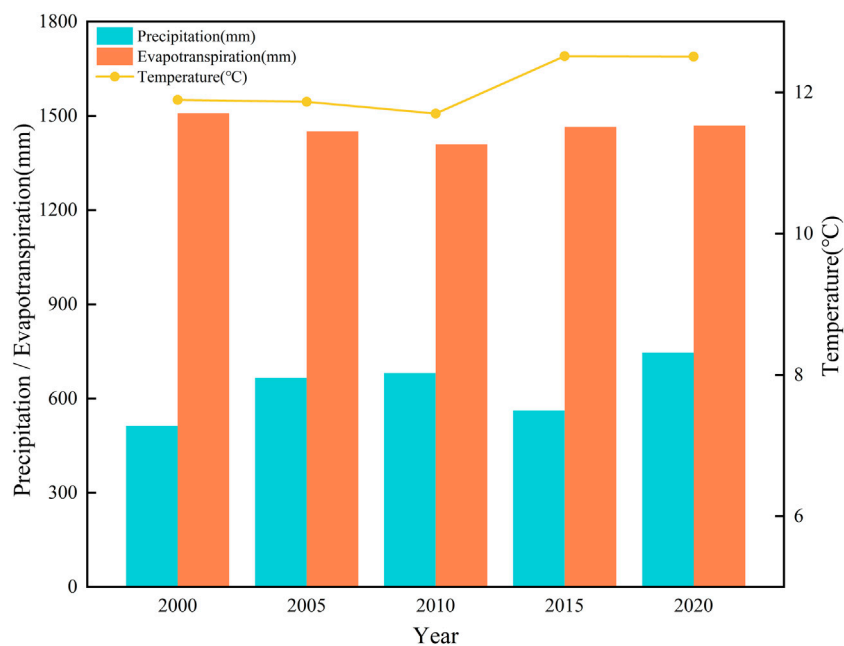
FIGURE 8
Changes in average temperature, precipitation and evapotranspiration in the Bohai Rim region during 2000−2020.

measures, and high intensity of urban construction, resulting in low SC function.

The human factors such as, development of technology, policy changes and LULC patterns are the main factors affecting ESs. From 2000 to 2010, crop varieties and planting technologies developed rapidly, and CP increased rapidly. In 2020, the Bohai Rim region faced multiple threats such as severe floods and COVID-19 epidemic, and the total CP declined. However, the government increased its support for crop production, implemented various policies to support agriculture and benefit farmers, actively responded to epidemics and disasters. So the impact of agricultural disasters on CP was limited. The LULC form is an important factor affecting regional ESs. Shandong Province is in the eastern coastal area and the middle and lower reaches of the Yellow River. It has superior geographical conditions and rich natural resources, with a small proportion of mountains, a vast area of cropland, and the CP level is high. Hebei and Liaoning provinces have widespread forest distribution and a large proportion of aquaculture. The effective cropland planting area is relatively small, and the degree of nearshore soil salinization is serious, resulting in low regional CP. Different LULC have different supply capacities for ESs due to differences in vegetation coverage, vegetation canopy height, canopy interception, soil moisture content, evapotranspiration capacity, and litter water holding capacity. The vegetation coverage of cropland and impervious land is low, the soil has a weak ability to absorb water, making it easy to form runoff (Guo et al., 2023), so the WY is relatively high. At the same time, these areas are either typical areas of urban expansion or key areas for agricultural planting. Urban construction and human activities have caused serious damage to HQ and LA. Due to the lack of artificial protection measures, SC and CS are also relatively low. Forests, shrubs and grasslands, due to their strong interception effect on precipitation and high evapotranspiration coefficients, are not conducive to water retention and have low WY level. However, due to its high vegetation coverage and less interference from human activities, the corresponding soil texture is less erodible, resulting in higher SC, HQ, and LA level.

4.3 Typical area analysis

The Bohai Rim region is vast, and due to differences in natural resource endowments and socio-economic factors among administrative, various ESs are highly heterogeneous and dynamic. For example, when comparing Qinhuangdao and Tianjin, the dominant ESs in Tianjin are provisioning services, while those in Qinhuangdao are regulating, supporting and cultural services (Table 6). The average CP in Qinhuangdao in the past 20 years is 80.28wt, accounting for 2.74% of the total area. While Tianjin has a greater advantage in CP, with an average of 166.95wt, accounting for 5.71%, about twice that of Qinhuangdao. However, the regulating service of Qinhuangdao is much higher than that of Tianjin, especially SC. The area of Tianjin is about 11,966.45 km^2 and the SC is 1632.15wt, while the area of Qinhuangdao is about 7750 km^2 and the SC is 7407.67wt, about 4.5 times those of Tianjin. In the past 20 years, the supporting and cultural service of Qinhuangdao have been much higher than the average level of the Bohai Rim region, while Tianjin is lower than it (Figure 9).

In the past 20 years, CP in Tianjin has continued to improve (Table 7). Compared with Qinhuangdao, the growth trend in Tianjin is stable, indicating that it has a stronger ability to resist natural risks and human interference, and is a key area for CP. WY

TABLE 6 Comparison of ESs between Tianjin and Qinhuangdao during 2000-2020.

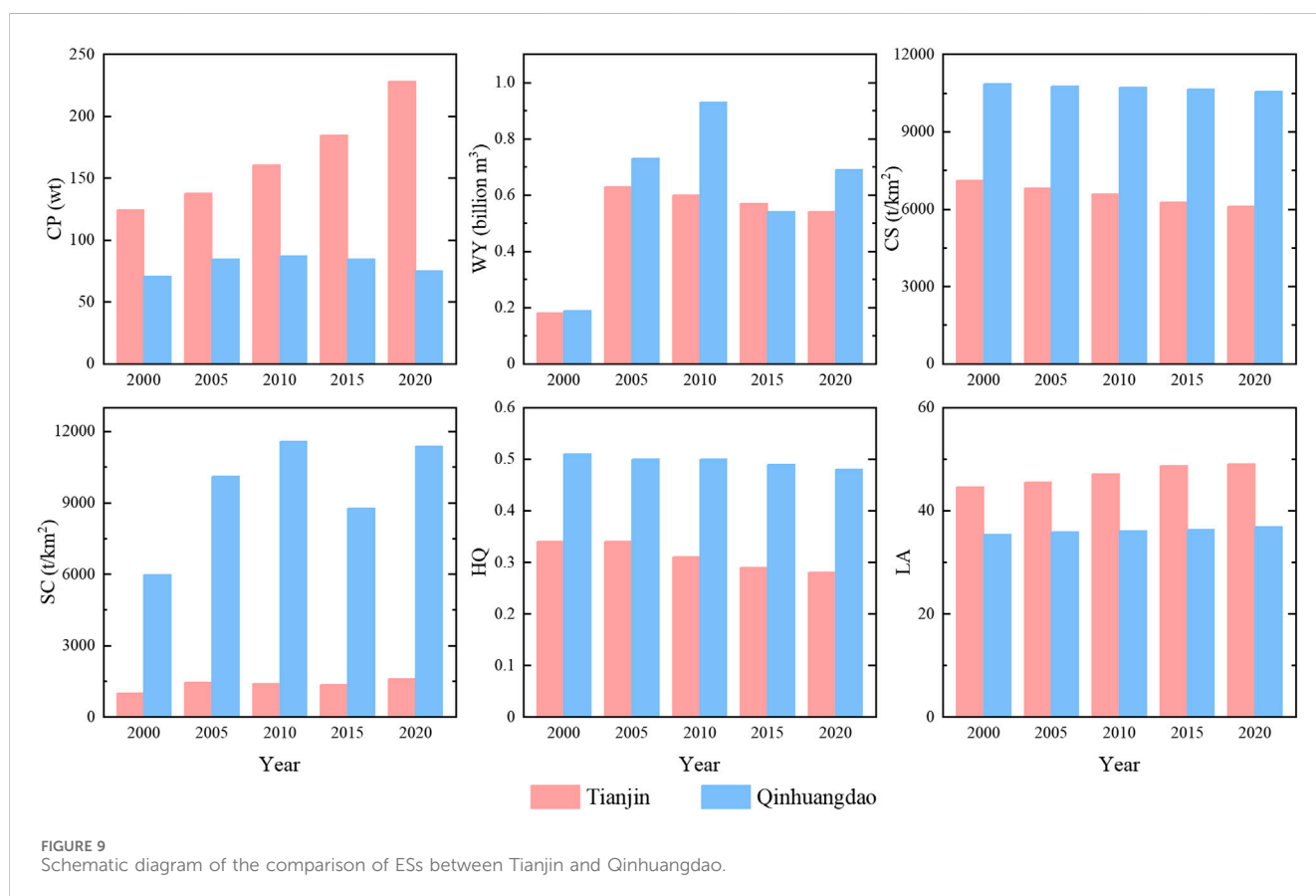| ES	Tianjin		Qinhuangdao	
	Total	Proportion	Total	Proportion
CP	834.78 (wt)	5.71%	401.34 (wt)	2.74%
WY	2.51 (billion m³)	2.55%	3.06 (billion m³)	3.10%
CS	7,870.44 (wt)	6.04%	8,299.72 (wt)	6.37%
SC	1632.15 (wt)	1.87%	7407.67 (wt)	8.50%
HY	0.312	—	0.496	—
LA	47	—	36.09	—

FIGURE 9
Schematic diagram of the comparison of ESs between Tianjin and Qinhuangdao.

in Tianjin has continued to decline since it increased to a maximum of 0.63 billion m³ in 2005, while the overall precipitation has not changed much from 2005 to 2020. It indicates that the WY in Tianjin is highly related to human activities. Although the amount of WY increased due to the dramatic expansion of impervious land, this high value has been offset by the reduction in cropland with similarly high WY capacity. At the same time, with the implementation of policy documents such as returning cropland to the lake, "Tianjin Land Use Master Plan (2006–2020)," "Tianjin Wetland Protection Ordinance," "Tianjin Wetland Nature Reserve Plan (2017–2025)," Tianjin has established an eco-friendly land use pattern that coordinates rivers, beaches, bays, lakes and seas. The internal structure and spatial layout of ecological construction and wetland protection land have been optimized, and many artificial wetlands have been integrated to form a wetland ecological network with higher connectivity and better aggregation, making WY in Tianjin more balanced and reducing the risk of floods caused by urban construction.

Qinhuangdao has distinct regional characteristic and is a famous coastal touristic area, leisure and holiday resort in China. Tourism and port logistics are its traditional advantageous industries. Qinhuangdao has outstanding capabilities in regulating, supporting and cultural services, with CS, SC, HQ, and LA all at a leading level in the Bohai Rim region (Table 8). This is mainly due to the warm temperate semi-humid continental monsoon climate in this region, which is greatly

TABLE 7 Tianjin ecosystem services.

ES	2000	2005	2010	2015	2020
CP (wt)	124.05	137.50	160.56	184.48	228.18
WY (billion m³)	0.18	0.63	0.60	0.57	0.54
CS (t/km²)	7,115.47	6,807.73	6,588.12	6,259.78	6,114.36
SC (t/km²)	1,006.15	1,448.69	1,410.78	1,361.04	1,593.04
HQ	0.34	0.34	0.31	0.29	0.28
LA	44.62	45.52	47.08	48.68	49.09

TABLE 8 Qinhuangdao ecosystem services.

ES	2000	2005	2010	2015	2020
CP (wt)	70.50	84.59	86.82	84.44	74.99
WY (billion m³)	0.19	0.73	0.93	0.54	0.69
CS (t/km²)	10,866.00	10,756.12	10,711.12	10,660.93	10,552.43
SC (t/km²)	5,976.48	10,102.59	11,565.89	8,759.95	11,386.54
HQ	0.51	0.50	0.50	0.49	0.48
LA	35.37	35.88	36.06	36.28	36.85

affected by the ocean. The climate is mild, with little rain and dryness in spring, warm and no scorching heat in summer, cool and sunny in autumn, and long and no severe cold in winter. In addition, the northern part of Qinhuangdao is dominated by mountainous and low hills, with forests, shrubs and grasslands as its main LULC types, which have good CS, SC and HQ capabilities. However, in the past 20 years due to the development of large-scale construction projects such as Qinhuangdao Economic and Technological Development Zone, Qinhuangdao Seaport Economic Development Zone, and Qinhuangdao Port, the ESs have degraded to varying degrees, among which CS has declined by 243wt, HQ by 4.92% and LA index has increased by 4.18%. In the future, Qinhuangdao should continue to leverage its regional advantages. The southeastern coastal areas should promote the concentrated and contiguous protection of agricultural land, strictly control the occupation of cropland by new construction, and revitalize existing construction land. The northern areas should effectively protect water sources and ecologically fragile areas, conduct comprehensive management of soil erosion and land degradation to ensure the continuous supply of ESs.

4.4 Policy planning suggestions

The natural environmental conditions and human activities are important factors influencing the regional landscape patterns and ESs. No single development policy can improve all landscape patterns and ESs. How to resolve the contradiction between protection and development is the core issue of ecological civilization construction (Li et al., 2022a). Firstly, people should

actively respond to the influence of natural factors. The Bohai Rim region has a temperate monsoon climate with uneven spatial distribution of rainfall, which is vulnerable to drought risks. Therefore, the provisioning service levels such as crop production and water yield in most areas fluctuate greatly. It is necessary to vigorously develop regional agricultural irrigation technologies and optimize agricultural irrigation strategies. The drip irrigation method will improve CP levels and save water resources (Wu, 2013). Water resources can be planned and managed to avoid waste through rainwater collection, wastewater recycling and freshwater protection. According to the characteristics of the ecosystem, sloping cropland and other cropland with low CP should be converted into forests and grasslands. In areas with heavy precipitation and strong soil erosion, forests should be considered priority, the areas with low precipitation and weak soil erosion, grasslands should be considered as priority basis. Selecting drought-resistant and water-saving species can also help alleviate water shortages. In addition, continuing to scientifically promote the implementation of water diversion projects is also one of the basic policies that local governments must adhere to, ensuring accurate and precise water diversion, refining water allocation plans, and strengthening precise scheduling from water sources to ecosystems.

Second, the irregular urban expansion should be restricted, and the urban landscape structure should be optimized. Correlativity study showed that rapid urbanization expansion and high-intensity land development are the main reasons for the ESs decline in the Yangtze River Delta urban agglomeration (Lu et al., 2024). Some scholars have compared the response of ESs in Shenzhen and Hong Kong to rural-urban transitions. And a persistent downward trend in the ESs was observed for both cities, although the decline in Shenzhen was much stronger than in Hong Kong. This was because as an island city, Hong Kong's urban expansion was much slower compared to Shenzhen's extremely rapid urbanization due to limitations in land availability (Xu et al., 2020). Therefore the results of ESs assessments should be incorporated into urban landscape planning. Adopting a green, low-carbon, and resource-saving urban development model. For example, when planning urban construction, attention should be paid to reducing the occupation of ecological land such as forests and grasslands, rationally constructing urban green spaces, integrating transportation networks, water networks, and ecological networks (Fu et al., 2022), configuring green infrastructure such as sponge cities to increase urban infiltration and reduce runoff (Yang et al., 2024), so as to improve WY levels, reduce land use intensity and ecological risks in urbanized areas. For urban parks and green spaces, it is necessary to arrange them in a hierarchical manner according to the spatial structure of population concentration, so as to form a complete park system, which can provide cultural services accurately while ensuring the fairness of green spaces, and ultimately promote the improvement of human wellbeing through ESs (Tu et al., 2019).

Third, people should strengthen the protection and restoration of key land types. Protect forests, shrubs, grasslands and wetlands with high regulating and supporting services, and maintain a sustainable supply of ESs by optimizing nature reserve

management strategies and implementing key ecosystem protection projects (Ma et al., 2021). At the same time, strengthening the landscape connectivity of key land types, aggregating small plots into larger patches can improve the supply level of ESs. To protect cropland resources, improve cropland quality, county-level people's governments should strengthen daily supervision of the conversion of cropland into construction land within the county area, and vigorously develop intensive cropland (Xing et al., 2020). When developing ecosystem optimization strategies, the resilience of different ecosystems should be considered (Zhao et al., 2019). For example, forest ecosystems tend to have stronger natural recovery capabilities and ecological resilience, while cropland, barren land, and wetland ecosystems are relatively fragile and less resilient (Liu et al., 2018; Seidl et al., 2014). Conducting refined design in this way will be more conducive to achieving sustainable management of regional ecosystems.

4.5 Limitations and prospects

This study uses InVEST model to evaluate ESs, the quality of evaluation depends on the accuracy of the LULC data classification. However, the accuracy of the Wuhan University CLCD dataset used in this paper is only 79.31%, and no more detailed secondary classification was performed when using it due to the difficulty in obtaining other parameters. In the future research, more detailed LULC classification and higher resolution, more accurate LULC datasets should be used.

In addition, this study only evaluated six key ESs that dominate the Bohai Rim region. Due to the large scope of study area, it cannot fully represent the overall ecological status of the region. In the future, scholars can add ESs that reflect regional characteristics, such as aquaculture and water purification. Moreover, the use of LA to characterize cultural services is usually limited to specific locations (Dou et al., 2022), and it is difficult to accurately reflect their overall situation. In the future, when conducting cultural service assessments, it is necessary to comprehensively select assessment indicators based on research needs and data availability. Finally, although the assessment results have been validated by other studies, the lack of measured data may still lead to certain uncertainties in the results. Future studies can support the assessment results by obtaining observational data from field surveys.

5 Conclusion

This study uses spatial and statistical data to quantify LULC, landscape pattern and ESs in the Bohai Rim region from 2000 to 2020 and analyses their change characteristics and influencing factors. The results show that from 2000 to 2020, the area of forest, water and impervious land increased, while the area of cropland, shrubs, grassland, and barren land decreased. From 2000 to 2015, the landscape in the Bohai Rim region were small and fragmented, complex and dispersed. Subsequently, during 2015–2020, landscape fragmentation weakened, the morphological structure was simplified, and the patches tended to aggregate. From 2000 to 2020, CP, WY and SC capacity show

an increasing trend, while CS, HQ and LA capacity show a decline trend. This study suggests that natural factors such as precipitation, temperature and altitude, as well as human factors such as technological progress, policy changes and LULC types are the main factors affecting the changes in landscape pattern and ESs. In the future, ecological managers and policymakers should focus on optimizing regional irrigation strategies and the methods of returning farmland to forest and grassland to reduce the constraints of natural factors on the supply of ESs; adopt methods such as configuring sponge cities, developing urban green spaces to limit the irregular expansion of cities and optimize urban landscape structure; continue to strengthen the protection and restoration of key land types, and protect high-quality forests, grasslands and wetlands to maintain a sustainable supply of ESs. The present study helps us to fully understand the changing characteristics and influencing factors of LULC, landscape pattern and ESs in the Bohai Rim region, and provide a basis for regional ecological restoration, ecological product value realization and territorial spatial planning.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

JL: Conceptualization, Formal Analysis, Investigation, Methodology, Writing–original draft, Writing–review and editing. WC: Project administration, Supervision, Writing–review and editing. HD: Project administration, Supervision, Writing–review and editing. ZL: Data curation, Software, Writing–review and editing. MX: Writing–review and editing. RS: Writing–review and editing. CL: Funding acquisition, Project administration, Supervision, Writing–review and editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1500045/full#supplementary-material

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